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TRANSFORMATIVE PULSED POWER SCIENCE AND TECHNOLOGY

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Final Report

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14. ABSTRACT
This study has focused on advanced concepts for generating high peak power, low energy, nanosecond time-scale pulses, and demonstrating that nanosecond pulsed power is an enabling technology. The project has also supported transitions of nanosecond pulsed power to important applications. Single, repetitive, and/or highly repetitive bursts of high peak power pulses can enable and/or enhance physical processes. Applications include combustion, compact, portable pulsed power generators, plasma-based accelerators, and bioelectric applications including basic studies of fundamental bioelectric processes, and useful therapies including cancer. Technology transfers include the initiation of two new companies: Transient Plasma Systems (TPS), started by students inspired by and supported by the AFOSR supported research, a US-based company that produces nanosecond pulse generators, now available to the DoD for applications including ignition and flow control, and for the future a valuable DoD asset, and another new venture under development for medical applications including skin disease therapies. 10 PhD student have graduated supported all or in part by this grant. The archival record includes 9 patents, 35 refereed and 13 conference papers.

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This study has focused on advanced concepts for generating high peak power, low energy, nanosecond time-scale pulses, and demonstrating that nanosecond pulsed power is an *enabling* technology. The project has also supported transitions of nanosecond pulsed power to important applications. Single, repetitive, and/or highly repetitive bursts of high peak power pulses can enable and/or enhance physical processes. Applications include combustion, compact, portable pulsed power generators, plasma-based accelerators, and bioelectric applications including basic studies of fundamental bioelectric processes, and useful therapies including cancer. Technology transfers include the initiation of two new companies: Transient Plasma Systems (TPS), started by students inspired by and supported by AFOSR supported research, and another new venture under development for medical applications including skin disease therapies. TPS is a US-based company to produce these nanosecond pulse generators, which are now available to the DoD for applications including ignition and flow control, and the company is now and for the future a valuable DoD asset. 10 PhD students have graduated with support all or in part from this project. A detailed archival record is provided in ≈35 refereed papers, 13 conference papers, 2 book chapters and 9 patents, listed below.

Archival publications (published) during reporting period (2009 to 2014):

Refereed Publications

1. Jiang, C., M.-T. Chen, C. Schaudinn, A. Gorur, P. T. Vernier, J. W. Costerton, D. Jaramillo, P. Sedghizadeh, and M. A. Gundersen, "Pulsed atmospheric-pressure cold plasma for endodontic disinfection", *IEEE Trans. Plasma Sci.* 37:1190-1195, 2009.
2. H. Chen, E. Kallos, P. Muggli, T. C. Katsouleas and M. A. Gundersen, "A High Density Hydrogen-Based Capillary Plasma Source for Particle-Beam-Driven Wakefield Accelerator Applications," *IEEE Trans. Plasma Sci.* **27** (3) 456-462 March 2009.
3. Chen, M.-T., L. G. De-Arco, F. N. Ishikawa, P. T. Vernier, C. Zhou, and M. A. Gundersen, Intracellular photoluminescence of carbon nanotube-fluorescein conjugates in human ovarian cancer cells, *Nanotechnology* 20:295101, 2009.
4. Chen, M.-T., C. Jiang, P. T. Vernier, Y.-H. Wu, and M. A. Gundersen, "Two-dimensional nanosecond electric field mapping based on cell electropermeabilization", *PMC Biophysics* 2 **(1),** 9, 2009.

5. Jiang, C., M.-T. Chen, C. Schaudinn, A. Gorur, P. T. Vernier, J. W. Costerton, D. Jaramillo, P. Sedghizadeh, and M. A. Gundersen, "Nanosecond pulsed plasma dental probe", *Plasma Processes and Polymers* 6:479-483, 2009.
6. Sanders, J. M., A. Kuthi, Y.-H. Wu, P. T. Vernier, and M. A. Gundersen, A linear, single-stage, nanosecond pulse generator for delivering intense electric fields to biological loads, IEEE Trans. Dielect. Elec. Ins. 16:1048-1054, 2009.
7. Wang, S., J. Chen, M. T. Chen, P. T. Vernier, M. A. Gundersen, and M. Valderrabano, "Cardiac myocyte excitation by ultrashort high-field pulses", Biophys. J. 96:1640-1648, 2009.
8. D. Singleton, J. Sinibaldi, C. Brophy, A. Kuthi and M. A. Gundersen, "Compact Pulsed Power System for Transient Plasma Ignition", IEEE Transactions of Plasma Science, IEEE Trans. Plasma Sci. 37 (12), 2275-2279, 2009.
9. Chen, M.T., L.G. De-Arco, FN Ishikawa, PT Vernier, C Zhou, and MA Gundersen, "pH-sensitive Intracellular Photoluminescence of Carbon Nanotube–Fluorescein Conjugates in Human Ovarian Cancer Cells," Nanotechnology, 20, 295101, 2009.
10. C Jiang, MT Chen, and MA Gundersen, "Polarity-Induced Asymmetric Effects of Nanosecond Pulsed Plasma Jets," Journal of Physics D: Applied Physics, 42, 232002, 2009.
11. PT Vernier, MA Gundersen, and M Valderrabano, "Cardiac Myocyte Excitation by Ultrashort High-Field Pulses," Biophysical Journal, 96(4), 1640-1648, 2009
12. J. M. Sanders, A. Kuthi, Y.-H. Wu, P. T. Vernier, and M. A. Gundersen, "A Linear, Single-stage, Nanosecond Pulse Generator for Delivering Intense Electric Fields to Biological Loads," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 16, pp. 1048-1054, 2009.
13. T. Shiraishe, T. Urushihara and M. Gundersen, "A Trial of Ignition Innovation of gasoline engine by nanosecond pulsed low temperature plasma ignition," Journal of Physics D: Applied Physics, 42 (2009) 135208 12pp.
14. Sozer, E.B., Jiang C., Umstattd R. J., Gundersen, M. A., "Quantum efficiency measurements of photocathode candidates for back-lighted thyratrons", Dielectrics and Electrical Insulation, IEEE Transactions on, 2009. 16(4): p. 993-998.
15. D. Singleton, S J. Pendleton, and M. A. Gundersen, "The role of non-thermal transient plasma for enhanced flame ignition in C2H4-air," J. Phys. D: Appl. Phys. 44 (2011) 022001.
16. Wu, Yu-Hsuan, M.A. Gundersen and P.T. Vernier, "Nanosecond Megavolt-Per-Meter Pulsed Electric Field Effects on Biological Membranes", Biophysical Journal 100(3), 502a, 2011.
17. D. Amaud-Cormos, P. Leveque, Y. Wu, J. M. Sanders, M. A. Gundersen, and P. T. Vernier, "Microchamber Set-up Characterization for Nanosecond Pulsed Electric Field Exposure", *IEEE Trans. Biomed. Eng*. 58:1656-1662, 2011.
18. J. M. Sanders, A. Kuthi, and M. A. Gundersen, "Optimization and Implementation of a Solid State High Voltage Pulse Generator that Produces Fast Rising Nanosecond Pulses," Dielectrics and Electrical Insulation, IEEE Transactions on, 18(4), 1228-1235, August 2011.
19. D. Singleton and M. A. Gundersen, "Transient Plasma Fuel-Air Ignition," *IEEE Transactions on Plasma Science*, vol. 39, no. 11, pp. 2214-2215, Nov. 2011.
20. D. Singleton, A. Kuthi, J. M. Sanders, A. Simone, S. J. Pendleton, and M. A. Gundersen, "Low Energy Compact Power Modulators for Transient Plasma Ignition," Vol. 18, No. 4, pp. 1084-1090, August 2011.
21. Yang, W., Y.-H. Wu, D. Yin, H. P. Koeffler, D. E. Sawcer, P. T. Vernier, and M. A. Gundersen, Differential sensitivities of malignant and normal skin cells to nanosecond pulsed electric fields, *Technology in Cancer Research and Treatment* 10:281-286, 2011.

22. S. J. Pendleton, J. Kastner, E. Gutmark, and M. A. Gundersen. "Surface Streamer Discharge for Plasma Flow Control Using Nanosecond Pulsed Power." *Plasma Sciences, IEEE Transactions on*, vol. 39 (11), pp. 2072-2073, 2011.
23. Batista Napotnik, T., Y.-H. Wu, M. A. Gundersen, D. Miklavcic, and P. T. Vernier, Nanosecond electric pulses cause mitochondrial membrane permeabilization in Jurkat cells, *Bioelectromagnetics*, in press, 2011.
24. Meng-Tse Chen, Stephen Swenson, Lewis De-Arco Gomez, Radu Minea, P. Thomas Vernier, Chongwu Zhou, Thomas C. Chen, and Martin A. Gundersen, "Carbon Nanotubes Inhibit Glioma Cell Migration In Vitro", submitted to BMC Cancer.
25. Yin, D., Yang, W.G., Weissberg, J., Goff, C.B., Chen, W., Kuwayama, Y., Leiter, A., Xing, H., Meixel, A., Gaut, D., Kirkbir, F., Sawcer, D., Vernier, P.T., Said, J.W., M.A. Gundersen, and H.P. Koeffler, "Cutaneous Papilloma and Squamous Cell Carcinoma Therapy Utilizing Nanosecond Pulsed Electric Fields (nsPEF)", PLoS ONE volume 7, issue 8, 2012.
26. E. Sozer, C. Jiang, and M. A. Gundersen, "Magnesium Based Photocathodes for Back-Lighted Thyratrons," IEEE *Transaction on Plasma Science, **40**, pp 1753-1758, 2012.*
27. S J Pendleton, A Montello, C Carter, W Lempert and M A Gundersen, "Vibrational and rotational CARS measurements of nitrogen in afterglow of streamer discharge in atmospheric pressure fuel/air mixtures", *J. Phys. D: Appl. Phys.* 45 495401 (2012).
28. S. J. Pendleton, S. Bowman, C. Carter, M. A. Gundersen, and W. Lempert. "The Production and Evolution of Atomic Oxygen in the Afterglow of Streamer Discharge in Atmospheric Pressure Fuel/Air Mixtures." *Journal of Physics D: Applied Physics*, vol. 46 305202, 2013.
29. Beier, Christopher W., Jason M. Sanders, and Richard L. Brutchey. "Improved Breakdown Strength and Energy Density in Thin-Film Polyimide Nanocomposites with Small Barium Strontium Titanate Nanocrystal Fillers."*The Journal of Physical Chemistry C* 117.14 (2013): 6958-6965.
30. Vernier, P.T., Z.A. Levine and M.A. Gundersen, "Water Bridges in Electropermeabilized Phospholipid Bilayers", Proceedings of the IEEE **101**, 494-504, (2013).
31. Y.-H. Wu, D. Arnaud-Cormos, M. Casciola, J. M. Sanders, P. Leveque, P. T. Vernier, "Moveable Wire Electrode Microchamber for Nanosecond Pulsed Electric-Field Delivery," *Biomedical Engineering, IEEE Transactions on* , vol.60, no.2, pp.489,496, Feb. 2013.
32. S. Romeo, Y.-H. Wu, Z.A. Levine, M.A. Gundersen, and P.T. Vernier, "Water influx and cell swelling after nanosecond electropermeabilization," *Biochimica et Biophysica Acta (BBA)-Biomembranes*, 2013.
33. B Shukla, V Gururajan1, K Eisazadeh-Far, B Windom, D Singleton, M A Gundersen and F N Egolfopoulos, "Effects of electrode geometry on transient plasma induced ignition", *J. Phys. D: Appl. Phys.* **46**, 205201, 2013.
34. Sjöberg, M., Zeng, W., Singleton, D., Sanders, J. and Gundersen, M.A., "Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-Mixed E85 DISI Engine Operation," *SAE Int. J. Engines* 7(4):1781-1801, 2014, doi:10.4271/2014-01-2.
35. A. Kuthi and J.M. Sanders, "Stepped Impedance Magnetic Compression Line Pulser", IEEE Transact. Plasma Sci., Vol. 42, No. 4, 2014, p984.

Book Chapters

1. C. Jiang, C. Schaudinn, D. E. Jaramillo, M. A. Gundersen, and J. W. Costerton, "A sub-microsecond pulsed plasma jet for endodontic biofilm disinfection," Z. Machala *et al.* eds. Plasma for Bio-

Decontamination, Medicine and Food Security, NATO Science for Peace and Security Series A: Chemistry and Biology, DOI 10.1007/978-94-007-2852-3_14, Springer, 2012.

2. J.M. Sanders, T. Tang, M.A. Gundersen, and G. Roth "High Power Switches: DC Switches," In *Handbook of Accelerator Physics and Engineering* (pp. 533-540). World Scientific Publishing Co. Pte. Ltd., New Jersey, 2013.

Conference Proceedings and Other Publications

1. J. M. Sanders, A. Kuthi, P. T. Vernier, W. Yu-Hsuan, J. Chunqi, and M. A. Gundersen, "Scalable, compact, nanosecond pulse generator with a high repetition rate for biomedical applications requiring intense electric fields," in *Pulsed Power Conference, 2009. PPC '09. IEEE*, 2009, pp. 1418-1421.
2. S. J. Pendleton, D. Singleton, A. Kuthi, M. A. Gundersen, "Compact Solid State Variable Amplitude High Repetition Rate Pulse Generator," IEEE Pulsed Power Conference, 2009.
3. D. Singleton, A. Simone, and M. A. Gundersen, "Optimization of Compact Power Modulators for Transient Plasma Ignition", IEEE International Power Modulators and High Voltage Conference, 254-257, May 2010.
4. J. M. Sanders, Y.H. Lin, R. Ness, A. Kuthi, and M. A. Gundersen, " Pulse Sharpening and Soliton Generation with Nonlinear Transmission Lines for Producing RF Bursts", IEEE International Power Modulators and High Voltage Conference, Proceedings of the 2010, 604-607, 2010.
5. Sozer E.B., Jiang C., Gundersen M. A.,. "Investigation of Gaseous Electron Multiplier-Based Triggering Units for Back-Lighted Thyratrons", Proceedings of 29th IEEE International Power Modulator and High-Voltage Conference, 553, 2010.
6. J. M. Sanders, A. Kuthi, and M.A. Gundersen, "Compact, Nanosecond Pulse Generators Based on Magnetic Pulse Compression and Diode Opening Switches," presented at the *4th Japan/U.S. Symposium on Pulsed Power and Plasma Applications*, Honolulu, HI, 2010.
7. E. B. Sozer, C. Jiang, A. Kuthi, J. M. Sanders, and M. A. Gundersen, "Compact Back-lighted Thyratrons for Applications in High Power Submicrosecond Pulse Modulators," presented at the at *4th Japan/U.S. Symposium on Pulsed Power and Plasma Applications*, Honolulu, HI, 2010.
8. J. M. Sanders, A. Kuthi, and M. A. Gundersen, "Pulse sharpening and soliton generation with nonlinear transmission lines for producing RF bursts," *Power Modulator and High Voltage Conference (IPMHVC), 2010 IEEE International*, pp.604-607, 23-27 May 2010.
9. J.M. Sanders, A. Kuthi and M. Gundersen, "Design and Optimization Techniques for the Generation of Intense, Ultrafast Pulses with Nonlinear Transmission Lines", IEEE Pulsed Power Conference, Aug. 2011.
10. Sanders, J. M., A. Kuthi, A., M.A. Gundersen, "A High Power Cascode Switch for Rapid and Efficient Energy Transfer at High Repetition Rates", *International Power Modulator and High Voltage Conference (IPMHVC),* 24-27 2012.
11. Y-H. Lin, D. Singleton, J. M. Sanders, A. Kuthi, and M. A. Gundersen "Pressure effects on transient plasma discharge in air," IEEE Pulsed Power and Plasma Science Conf. San Francisco, P1-25, 2013.
12. "Stepped Impedance Magnetic Compression Modulator," A. Kuthi, J.M. Sanders, and M.A. Gundersen, Vacuum Electronics Conference, IEEE International, Monterey, CA 22-24 April 2014, pp193-194.
13. "Core Reset Considerations of the Stepped Impedance Magnetic Compression Modulator," A. Kuthi, J.M. Sanders, and M.A. Gundersen, Power Modulator Conf., Santa Fe, NM, June 1-5, 2014, to appear.

Invited Presentations, Partial List

1. M..A. Gundersen, “Transient Plasma Ignition with Nanosecond Pulsed Power”, Duke University, May 27, 2010.
2. M.A. Gundersen, “Nanosecond Pulsed Power: Therapy for Cancer”, Duke University, May 27, 2010.
3. M. Gundersen, “The Nanoworld”, Categorically Not!, Santa Monica, January 16, 2011.
4. M. Gundersen, “Nanosecond Pulsed Power: Rocket Science, Cancer, and the Movies”, Old Dominion University, January 26, 2011.
5. D. Singleton, J. Sanders and M. Gundersen, “Transient Plasma for Improved Combustion Efficiency in Engines”, Invited poster presentation, 2011 ARPA E Energy Innovation Summit, Arlington VA, Feb 28, 2011.
6. M.A. Gundersen, “Cancer, Rocket Science, and the Movies: Research in Nanosecond Pulsed Power” The Naval Postgraduate School, Monterey CA, April 29, 2011.
7. M.A. Gundersen, “Pulsed Power and Transient Plasma Ignition”,ARPA-E Workshop on Small Scale Distributed Generation, Arlington VA, June 2, 2011.
8. M.A. Gundersen, “Transient Plasma: Energy, Engines, and Aerospace Applications”, Workshop on Atmospheric Pressure Weakly Ionized Plasmas for Energy Technologies, Flow Control and Materials Processing, Princeton University, Aug 23, 2011.
9. “Transient Plasma: Energy, Engines, and Aerospace Applications”, with P.T. Vernier and C. Jiang, Plenary presentation for the 2012 IEEE Intl. Conference on Plasma and Nuclear Science, Edinburgh Scotland, July 2012.
10. M. Gundersen, “Combustion and Aerospace Applications of Nanosecond Pulsed Power–Generated Transient Plasma”, presented to the Aerospace and Mechanical Engineering Department at U. of Arizona, Nov. 1 2012.
11. Sanders, J. M., “Megawatts from Millijoules: A Discussion on the Science and Engineering of Pulsed Power Devices and Their Application for Research into Nonequilibrium Phenomena,” Old Dominion University, Norfolk, VA October 29, 2013.
12. M. Gundersen, Fokion Egolfopoulos, Andy Kuthi, Dan Singleton, Jason Sanders, Yung-Hsu Lin, and Angus McColl, “TCC Institute for Emissions Reduction from Marine Diesel Engines”, California Maritime Leadership Symposium, February 21, 2013, Sacramento CA.
13. M. Gundersen, "Transient Plasma for Green Technologies: Reduced Emissions, Greenhouse Gas Reduction, and Improved Combustion Efficiencies", 60th Annual AVS International Symposium and Exhibition (AVS 2013), Oct 31-Nov 1, 2013, Long Beach, CA.
14. Y-H Lin, A Kuthi, W. Schroeder, D Singleton, J Sanders and M A Gundersen, Intl. Conf. on Plasma Science (ICOPS), “Non-Equilibrium Plasmas In Fuel-Air Mixtures Generated By Half Of A Microwave”, May 27, 2014, Washington D.C.

Contributed Presentations without papers, Partial List

Presentations accompanied by conference papers are included in “Conference Papers and Other Publications”, and are not included below.

1. S. Y. Kim, J. M. Sanders, E. B. Sozer, Y. H. S. Lin, Q., A. Kuthi, and M. A. Gundersen, "RF Enhanced PECVD System For CNT Field-Emitter Cathode Array Deposition," in International Conference on Plasma Science, San Diego, CA, 2009.

2. J. W. Luginsland, D. Singleton, M. Gundersen, C. Brophy, J. Sinibaldi, E. Barbour, D. Waxman, R. Hanson, “The Role of Water in Transient Plasma Ignition for Combustion,” IEEE 36th International Conference on Plasma Science, 2009
3. D. R. Singleton, M. A. Gundersen “Study of the Volumetric Effect of Transient Plasma Ignition in Quiescent Ethylene-Air,” IEEE 36th International Conference on Plasma Science, 2009.
4. Craviso, G. L., G. Maalouf, S. Choe, M.-T. Chen, D. McPherson, I. Chatterjee, M. A. Gundersen, and P. T. Vernier, Nanosecond electric pulse stimulates catecholamine release from chromaffin cells, Bioelectromagnetics Society 30th Annual Meeting, San Diego, 2008.
5. M. Anderson, M. A. Gundersen, J. M. Sanders, D. R. Singleton, and A. Waterhouse, "Effects of Pulsed Energy Field Treatments on White Wine Grapes," in *Annual Meeting Poster Session, American Society for Enology and Viticulture*, Napa, California, 2009.
6. Sozer, E.B., Jiang C., and Gundersen M.A.. “Investigation of Gaseous Electron Multipliers with Magnesium Photocathodes for Optical Triggering Of Back-Lighted Thyratrons”, International Conference on Plasma Science, 2010.
7. “An atmospheric pressure non-thermal plasma needle for endodontic biofilm disinfection,” C. Jiang, C. Schaudinn, D. E. Jaramillo, P. Webster, M. A. Gundersen, and J. W. Costerton, The 38th IEEE International Conference on Plasma Science (ICOPS) and 24th Symposium on Fusion Engineering (SOFE), Chicago, USA, June 20, 2011.
8. Wu, Y.-H., M. A. Gundersen and P. T. Vernier, “Biophotonic Studies of Intracellular Responses to Nanosecond, Megavolt-per-meter, pulsed Electric Field”, Poster presentation, Optics in the Life Sciences, Monterey CA, April 5, 2011.
9. Wu, Y.-H., M. A. Gundersen, and P. T. Vernier, Nanosecond, megavolt-per-meter pulsed electric field effects on biological membranes, Biophysical Society Annual Meeting, Baltimore, 2011.
10. Y.-H. Wu, D. Arnaud-Cormos, M. Casciola, J.M. Sanders, P. Leveque, and P.T. Vernier, P. T., “Versatile broadband electrode assembly for cell electroporation,” In *Engineering in Medicine and Biology Society (EMBC), 2012 Annual International Conference of the IEEE* (pp. 2563-2566). IEEE, 2012.
11. S. J. Pendleton, D. Singleton, Y. H. Lin, A. Kuthi, and M. A. Gundersen. “Nanosecond Pulsed Power and Transient Plasma Ignition.” Invited Talk at the *Plasma Assisted Combustion MURI Review*, The Ohio State Uniersity, November 2011.
12. S. J. Pendleton, S. Bowman, D. Singleton, J. Watrous, I. Adamovich, W. Lempert, C. Carter, M. A. Gundersen. “Oxygen Pathways in Streamer Discharge for Transient Plasma Ignition.” Oral Presentation at the *64th Gaseous Electronics Conference*, Salt Lake City, UT, November 2011.
13. S. J. Pendleton, J. Watrous, M. A. Gundersen. “Temporal Temperature Evolution of Streamer Discharge in Air.” Oral Presentation at the *38th IEEE International Conference on Plasma Science*, Chicago, IL, June 2011
14. S. J. Pendleton and M. A. Gundersen. “Optical Diagnostics on Transient Plasma Ignition.” Poster Presentation at the *38th IEEE International Conference on Plasma Science*, Chicago, IL, June 2011
15. S. J. Pendleton, D. Singleton, J. M. Sanders, A. Kuthi, and M. A. Gundersen. “Transient Plasma Ignition for the Improvement of Combustion.” Poster Presentation at the *2011 Aerospace Thematic Workshop:Fundamentals of Aerodynamic Flow and Combustion Control by Plasmas*, Les Houches, France, March 2011.
16. S. J. Pendleton, E. Mintoussov, N. A. Popov, S. Starikovskaia, and M. A. Gundersen. “Fast Gas Heating in Fast Ionization Wave Discharge: Experiment and Modeling.” Oral Presentation at the *37th IEEE International Conference on Plasma Science*, Norfolk, VA, June 2010.

17. YH Lin, D. Singleton, J. Sanders, A. Kuthi and M.A. Gundersen, "Experimental study of pulsed corona discharge in air at high pressures", 65th Annual Gaseous Electronics Conference, Austin TX, Oct 26, 2012.
18. S.J. Pendleton, A. Kuthi, H. Chen, P. Muggli, M.A. Gundersen, "Pulsed high-density hydrogen plasma source for wakefield accelerator applications," IEEE Pulsed Power and Plasma Science Conf. San Francisco, P5-27, 2013.
19. Y-H. Lin, D. Singleton, J. M. Sanders, A. Kuthi, and M. A. Gundersen "Pressure effects on transient plasma discharge in air," IEEE Pulsed Power and Plasma Science Conf. San Francisco, P1-25, 2013.

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Extensions granted or milestones slipped, if any: None

Include any new discoveries, **inventions, or patent disclosures** during this reporting period (if none, report none):

Patents Granted and Applied for

1. Sanders, J., Kuthi, A., and Gundersen, M.A., *Nanosecond Aircore Pulse Generator with Scalable Pulse Amplitude*, Filed by USC on May 22, 2009
2. Sanders, J., Jiang, C., Kuthi, A., and Gundersen, M. A., *Broadband Voltage and Current Measurement Device for High-Voltage, Nanosecond Electric Pulses*, Filed by USC on May 22, 2009
3. Sanders, J., Singleton, D., Gundersen, M.A., U.S. Patent Application No. 12/607,844, Treatment of food must with Low Energy Pulsed Electric Field
4. Patent Awarded: Kuthi, A. and Gundersen, M.A., High Voltage Nanosecond Pulse Generator using Fast Recovery Diodes for Cell Electro-Manipulation, Patent No.: US 7,767,433, Aug. 3, 2010
5. High voltage nanosecond pulse generator using fast recovery diodes for cell electro-manipulation (U.S. Patent 7,767,433 B2, Aug. 3, 2010)
6. High voltage nanosecond pulse generator using fast recovery diodes for cell electro-manipulation (U.S. Patent 7,901,929 B2), Mar. 8, 2011)
7. High voltage nanosecond pulse generator using fast recovery diodes for cell electro-manipulation (U.S. Patent 7,901,930 B2), Mar. 8, 2011) *(there are three patents with the same name)*
8. J Sanders, A Kuthi, MA Gundersen, WH Moore, "Nanosecond pulse generator with a protector circuit", 2012, US Patent 8,120,207
9. J Sanders, A Kuthi, MA Gundersen, WH Moore, "Nanosecond pulse generator", 2012, US Patent 8,115,343

Representative recent achievements specifically related to nanosecond pulsed power:

1) Development of a new type of magnetic pulse compression (MPC) line that is capable of achieving voltage multiplication at 100% energy transfer using less magnetic material than traditional lines. Sharing similarities with the stepped impedance transmission line invented by I. Smith and S. Darlington, as well as Fitch's resonant voltage doubler, this line makes use of precharged capacitors. An energy and charge conservation analysis shows that properly choosing the pre-charge voltage of downstream capacitors enables voltage multiplication at full energy transfer. This is not possible for traditional magnetic compression lines, which can only achieve voltage multiplication at the expensive of energy transfer. Applying the analytical results to a practical four stage line has resulted in a design that is capable of producing an output pulse with a nominal voltage gain of 5 and full energy transfer to the load. This is a meaningful improvement over traditional pulse compression lines, which sacrifice 25% of the initially stored energy for a 50% increase in voltage amplitude per stage.

2) Reduction of jitter in high rep rate MPC systems to less than 1.5% by means of a simple core reset method that requires only a single snubber. Amplitude jitter is frequently a problem in high rep rate systems due to difficulties associated with resetting the cores to a consistent initial flux. As the time between output pulses reduces, core reset circuitry typically becomes more complex as higher voltages are required. In order to avoid additional high voltage circuitry that would be required for an active reset approach, a simple method has been developed that only requires a simple resistive snubber. A flux conservation analysis indicates that, provided the given reset time is approximately 5 times larger than the snubber's time constant, choosing a snubber with a value C^*V_o/Φ where C is the stage's capacitance, V_o is residual voltage, and Φ is the magnetic flux, will fully balance the core's flux while leaving no residual energy in the system. This approach was applied to a 10kHz unit, and the output jitter was reduced from 40% (in the case of no reset or inadequate reset) to less than 1.5%. The tradeoff to this approach is increased dissipation, however, for applications with modest average power (< 1kW), this approach significantly reduces complexity. It also reduces system size for modest rep rates, roughly 10 kHz and below. This approach can be utilized over a large range at a fixed energy cost, up to the point where the snubber's time constant begins to approach the resonant period of the compression stage. At this limit, the fraction of the stored energy that must be reserved for reset grows proportionally with $(PRR)^2$, where PRR is the repetition rate.

3) Improved design for electromagnetic compatibility and the development of diagnostics for measuring instantaneous power delivered to complex loads. Practical use of these systems often takes place in a lab environment in the vicinity of sensitive equipment that is easily perturbed by EMI produced by fast rising, high voltage pulses. These laboratory experiments also frequently involve pulsing complex loads that have unknown, time-varying impedances, making it difficult to measure energy that is delivered on timescales of a few nanoseconds. We have addressed these challenges in the last year by redesigning the layout and subsystem assembly of our high repetition rate units (those most likely to generate EMI) and by designing a custom broadband, high voltage rated power monitor that provides time-resolved voltage and current traces for risetimes as fast as 2 ns. This power monitor is modular, enabling the user to connect it directly to the load, thus alleviating the need to correct for propagation effects that cable interconnect has on fast pulses measured at the output of the generator. This system has proven to be electrically quiet, producing no observable noise in multiple experiments in the last 12 months, including two at the Combustion Research Facility at Sandia National Laboratory and one at the Naval Postgraduate School.

DoD Benefits:

The research benefits the DoD in High Power Microwave (HPM) systems; ultra-wideband radar; wireless power transmission; compact, efficient, and versatile HPM components; high bandwidth sources capable of producing high power RF bursts; reduced size and weight to enable mobile applications that are not now possible. **Small engines and HPM:** We anticipate that among the most important benefits will be pulse generation for 1) ignition in small engines, with preliminary results demonstrated in a Capstone project overseen by the WPAFRL (Schauer) and studies elsewhere, including recent collaboration with Sandia National Laboratory, and 2) Design and engineering leading to miniaturization of pulsed power for HPM, through collaboration with the AFRL at Albuquerque (Shiffler, Heidger). **Ancillary DoD Benefits:** Under AFOSR support, enabling nanosecond pulsed power innovations have been demonstrated in collaborations with experts in areas including combustion and medicine. For USC pulsed power research collaborators have included, for combustion collaborations have occurred with the Air Force (primarily WPAFRL), Nissan, Sandia National Laboratories Livermore. Biomedical applications work with cancer research at Cedars Medical Research Center (Koeffler, Marcu), cardiovascular with UCLA and Houston Methodist (Valderrabano), and translational through the Alfred Mann Institute at USC, with Old Dominion U., now include patient studies at Huntington Hospital in Pasadena CA for skin conditions. Our group has also performed preliminary, yet very promising studies of the effects of field-assisted juice extraction from wine grapes in collaboration with the A. Waterhouse group at U.C. Davis Dept. of Enology and Viticulture.

Graduated PhD Students 2009-2014

Electrical Engineering unless otherwise indicated, all or partially supported by AFOSR grant (FA9550-09-1-0458).

Charles Cathey	2009	Transient plasma for combustion: physics and applications
Yu-San Liu (Chem E)	2009	Quantum dot fluorescent indicators for nanoelectroperturbation studies of cancer cells
James Liang (Chem E)	2009	Functionalization of carbon nanotubes for introduction into cancer cells
Jessica Hao Chen	2010	Compact Back-lighted thyratron switches
Meng-Tse Chen (Mat Sci)	2010	Biophotonic studies of nanosecond pulsed field induction of apoptosis in cancer cells
Daniel Singleton	2010	Transient plasma ignition
Jason Sanders	2011	Compact pulsed power
Esin Sozer	2011	Compact back-lighted thyratron switches
Scott J. Pendleton (Physics)	2012	Experiments for understanding transient plasma ignition
Zachery Levine (Physics)	2013	Theoretical Studies of Lipid Bilayer Electroporation
Ming-Chak Ho (Physics)	2013	Molecular dynamics simulation of electroporation in phospholipid bilayer
Yu-Hsuan Wu (Chem E)	2014	Biophotonic Studies of Intracellular Responses to Nanosecond, Megavolt-per-meter, pulsed Electric Field
Yung-Hsu Lin (Physics)	2014	Physics of transient plasma at Higher Pressures

Ho, Wu, Levine and Liu were primarily directed by P. Thomas Vernier.

Awards

Martin Gundersen received the Sol Schneider award of the 2010 IEEE Power Modulator and High Voltage Conference “For Continuing Technical and Administrative Leadership in the Power Modulator and High Voltage Communities”.

Jason Sanders was recipient of the 2011 IEEE Nuclear Plasma Sciences Society Student Paper Award (Best paper award for both the 2011 IEEE Conference on Plasma Science and the 2011 IEEE Pulsed Power Conference). The title of the paper is “Design and Optimization Techniques for the Generation of Intense, Ultrafast Pulses with Nonlinear Transmission Lines”

Appendix 1: Pulsed Power Specific Future Research Summary

Based on research conducted to date, we believe there is potential for extending these results to shorter temporal regimes, i.e. picosecond pulsed power, will further impact enabling pulsed power applications with benefits to energy efficiencies and other areas such as bioelectrics. Energy per pulse will be

Research into High Voltage, Picosecond Pulse Generation		
Research Topic	**Potential Methods**	**Notes**
Picosecond Risetime (>1kV amplitude)	Ferrite Shocklines	Rep rate limited by magnetic reset circuitry. NiZn ferrites theoretically capable of reducing risetimes to 30 ps, but practical designs require amplitude ~50kV to achieve such short times.
	Optically triggered Photoconductive Solid State Switch	Rep rate limited by recombination time/dissipation (avalanche mode) or by dissipation (linear mode). Linear mode operation is a good candidate for a system with adjustable FHWM, but switch will likely have high on-state impedance.
	Solid state avalanche switches	Rep rate limited by recombination time/dissipation. FWHM is determined by circuit timeconstants, not by switch.
	Pressurized spark gap	Rep rate limited by recombination time (typically longer than solid state devices, depending on geometry).
Picosecond FHWM (>1kV amplitude)	Optitcally triggered Photoconductive Solid State Switch	Linear mode operation enables turn-off capability --> Fast laser with sufficient energy at appropriate wavelength could make fast electrical pulse. High on-state impedance is a likely trade-off.
	Appropriate circuit design + other picosecond risetime switches	Circuit timeconstants less than 1 ns --> ps FWHM. Requires careful design, likely custom machined components
	Tailcut switch	Employ a shunt switch that triggers and shorts excess energy to ground --> likely unclean pulse with resonance on tail.

Research into High Voltage Pulse Generation		
Research Topic	**Details**	**Notes**
Precharged Magnetic Pulse Compression	Precharged capacitors as a means to increasing compression gain	Andy Kuthi has written up notes on the theory of this approach
Circuit synthesis to optimize diode switching	Analytical project focused on maximizing diode pumping efficiency. Measured data on diode performance should guide design.	Jason Sanders has worked on this, but there is opportunity to expand upon it.

Research into Highly Repetitive (High Rep Rate) Pulse Generation		
Research Topic	**Details**	**Notes**
System miniaturization via increased efficiency	Inefficiencies of existing designs result in larger system size and weight for high rep rate systems. Look into way to increase efficiency / refine design to work towards reducing system size and weight.	As system efficiency increases, load matching becomes increasingly important because highly efficient systems won't dissipate energy quickly. Load matching is difficult when driving plasma sources, so an actively switched dissipation circuit may be required for some applications.
System miniaturization via optimal architecture design	Practical systems have specifications for the voltage and current ratings of prime power sources (often times low voltage, high current). For these cases, look at power conversion and pulse generator design together in an effort to find the most compact design.	In general high voltage switching is the easiest, b/c peak currents will be lower. i^2R losses are dominant, so it's desirable to avoid high current where possible.
Highly repetitive, flat-top, picosecond risetime pulses at modest votlages (5-10kV)	A number of DoD and DoE applications require fast rising, flat top pulses that can delivered to a load at high repetiton rates (100 kHz)	Jason Sanders has done work on 5 kV, flat top pulses at 100kHz and can provide feedback on approaching this topic.

Research into Materials / Devices for Pulsed Power		
Research Topic	**Details**	**Notes**
Diode Opening Switch	These switches can generate very high dV/dt pulses at high voltage. Diode geometry and doping profile significantly affect switching time. Combined approach of analysis/simulation can guide doping profile design, which can then be built and tested.	Recombination rate (reverse recovery time) is important, and needs to be long -- negligible recombination on 100ns timescale.
Closing Switches	Photoconductive solid state switches / avalance diodes / spark gap switches. All suitable for producing sub-ns risetime pulses.	See Picosecond Risetime Section above.
Nonlinear Materials for Pulse Compression	The nonlinear characteristic of ferri(ferro)magnetic and ferroelectric materials are useful for pulse compression. These can be used to create nonlinear transmission lines for risetime compression, and potentially for soliton generation.	Historically magnetic materials are desirable for nonlinear transmission lines b/c ferrites exhibit significant nonlinearity at high freq. and have low eddy loss. Dielectric materials that exhibit significant nonlinearity tend to be high epsilon (--> low cutoff frequency) and lossy at high frequency. The recent availability of BaTiO3 nanoparticles may open up a new approach. Research could look at how BaTiO3 nonlinearity changes with particle size and density.
Materials/growth methods for high energy density capacitors	High energy density capacitors are important for miniaturizing pulse genrator size. Increasing energy density can be achieved by either increasing the dielectric constant or by increasing voltage rating.	Dielectrics in IC can withstand very high E-fields before breakdown. Can the growth methods/materials be adopted for pulsed power applications. How does voltage hold-off change as dielectric thickness increases?